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# Reversible Reaction of CO<sub>2</sub> with Superbasic Ionic Liquid [P<sub>66614</sub>][benzim] Studied with *In Situ* Photoelectron Spectroscopy

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## ABSTRACT

Ionic liquids (ILs) are of significant interest as CO<sub>2</sub> capture agents, and one subgroup of ILs that has shown particular promise is that of superbasic ILs. They can absorb large quantities of CO<sub>2</sub> in the dry state, but some will have a diminished CO<sub>2</sub> capacity when pre-wetted. In the work presented here, the superbasic IL trihexyl-tetradecylphosphonium benzimidazolide, or [P<sub>66614</sub>][benzim], was exposed to 3 mbar CO<sub>2</sub>, 2 mbar H<sub>2</sub>O vapor, and a CO<sub>2</sub> + H<sub>2</sub>O gas mixture; and investigated using near-ambient pressure X-ray photoelectron spectroscopy. The results show that the IL reacts with CO<sub>2</sub> to form carbamate, and that the reaction is reversible through reduction of the surrounding gas pressure. Regardless of whether the IL was exposed to CO<sub>2</sub> or H<sub>2</sub>O vapor first, the presence of H<sub>2</sub>O under these experimental conditions does not significantly hinder the IL's ability to absorb and react with CO<sub>2</sub>. Furthermore, the IL appears to preferentially react with CO<sub>2</sub> over H<sub>2</sub>O vapor.

## INTRODUCTION

International commitments to a reduction in global CO<sub>2</sub> emissions could be in part met by CO<sub>2</sub> sequestration and storage, or utilization<sup>1-3</sup>. As a result, there is a pressing desire to identify stable, practical and economically viable methods to achieve this. Currently, the most widely used industrial solution is monoethanolamine (MEA)<sup>4-5</sup>. When MEA reacts with CO<sub>2</sub>, it forms a carbamate species (COO<sup>-</sup>) and a protonated MEA species (see Scheme 1). MEA is relatively cheap as a bulk solvent, but is extremely corrosive and requires a relatively large amount of energy to regenerate it following CO<sub>2</sub> capture<sup>6</sup>. Both of these factors contribute to increased costs where CO<sub>2</sub> is required to be removed.

Ionic liquids (ILs) have been widely investigated as potential CO<sub>2</sub> capture agents due to their advantageous properties, including ultra-low vapor pressures and excellent thermal stability. They are relatively easy to handle, and the regeneration of ILs after CO<sub>2</sub> capture is a relatively low energy process<sup>6-7</sup>. ILs can capture CO<sub>2</sub> via chemisorption or physisorption, and in previous years, attempts to improve the CO<sub>2</sub> capture capabilities of ILs have been successful with the addition of amine functional groups<sup>8</sup>. These react with CO<sub>2</sub> in much the same way as MEA (see Scheme 1). However, a problematic repercussion of CO<sub>2</sub> absorption in amine-functionalized ILs is an increase in their viscosity, which tends to inhibit further CO<sub>2</sub> absorption.

Current research also suggests that the presence of water in the gas stream can assist or hinder the ability of an IL to capture CO<sub>2</sub>, depending on the constituent ions of the IL and the concentration of water. While the addition of water in amine-functionalized ILs reduces their viscosity, it also results in a decrease in CO<sub>2</sub> uptake<sup>9</sup>. The decrease in CO<sub>2</sub> uptake is attributed to protonation of the pyridine-like N group, which reduces the number of available sites for CO<sub>2</sub> to chemically bind<sup>9</sup>. The addition of small amounts of water has shown to improve the CO<sub>2</sub> capture

capabilities of some ILs. Phenolate-based ILs, for example, capture CO<sub>2</sub> through chemisorption, and the addition of 2 wt% H<sub>2</sub>O almost doubled the molar CO<sub>2</sub> absorption<sup>10</sup>. For acetate-based ILs, which capture CO<sub>2</sub> through physisorption, the molar absorption increased eightfold with the addition of 0.35 molar fraction of H<sub>2</sub>O<sup>11</sup>.

In recent years, so-called superbasic ILs (SBIL) have attracted particular interest. These ILs consist of an imidazolide anion (a deprotonated and negatively charged aromatic ion). Reaction with CO<sub>2</sub> leads to the exothermic formation of carbamate at one or more of the deprotonated amine sites<sup>6, 12</sup>. Studies of superbasic ILs by various groups have shown an excellent capacity for CO<sub>2</sub> capture, with molar ratios ( $n_x$ ) of up to 1.6:1 ( $n_{\text{CO}_2}:n_{\text{IL}}$ )<sup>6</sup>. In addition, these superbasic ILs do not undergo a large increase in viscosity upon CO<sub>2</sub> saturation, which makes them potentially useful in large-scale applications. An experimental and theoretical study of superbasic ILs showed that the IL, trihexyl-tetradecylphosphonium benzimidazolide ([P<sub>66614</sub>][benzim] - see Figure 1), was able to absorb equimolar quantities of CO<sub>2</sub> in the dry state, but exhibited a reduced capacity for CO<sub>2</sub> absorption if the IL was pre-wetted<sup>6, 12</sup>. This could be problematic if they are to be considered for CO<sub>2</sub> capture on an industrial scale, since industrial flue gases consist of a complex mixture of gas molecules, including CO<sub>2</sub> and H<sub>2</sub>O.

X-ray photoelectron spectroscopy (XPS) has been a useful tool in the analysis of surface reactions, and surface electronic structure of solids for many years<sup>13-14</sup>. The extremely low vapor pressure of ILs has also meant that in recent years studies of liquid surfaces have been possible<sup>15-18</sup>. Interactions between gases and ILs have been studied using XPS, but at low temperatures. The gas and the IL need to be cooled together (which forms a glassy structure), then gently heated to monitor gas desorption from the IL<sup>19</sup>. This process is necessary because, at the extremely low pressures required for XPS, gases often do not remain trapped or ad/absorbed in

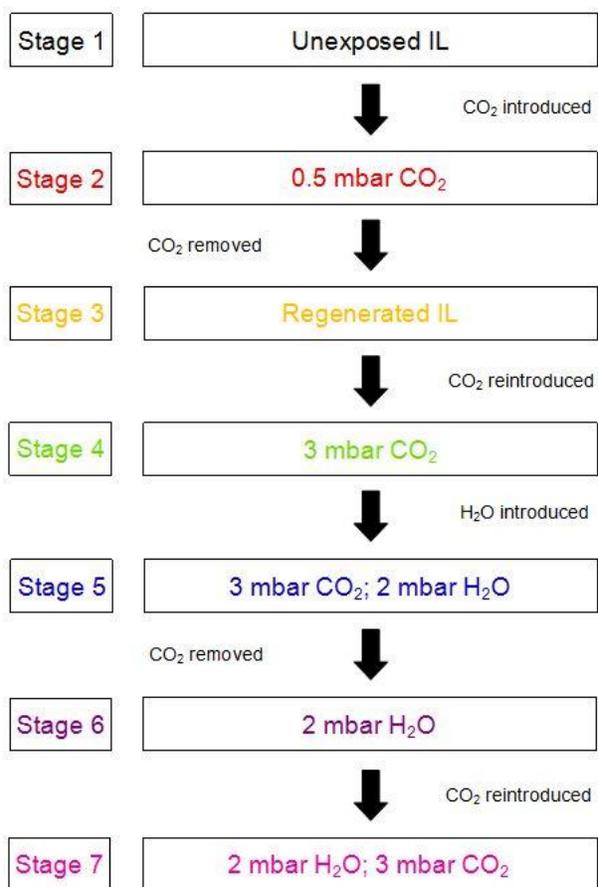
any appreciable amount at ambient temperatures. Rivera-Rubero and Baldelli, for example, showed that water can be removed from the IL 1-butyl-3-methylimidazolium tetrafluoroborate ([C<sub>4</sub>C<sub>1</sub>Im][BF<sub>4</sub>]) at pressures of  $<1 \times 10^{-5}$  mbar at room temperature<sup>20</sup>. The recent availability of near-ambient pressure XPS (NAPXPS) has opened up the possibility of measurements of liquid surfaces in gas pressures of up to a few tens of mbar<sup>4, 8, 21-23</sup>. In our own work<sup>24</sup> and in work of groups such as the Newberg group<sup>25-27</sup>, NAPXPS has allowed for surface-sensitive studies of the interactions between gas molecules and ILs. Herein, we examine the reaction of the superbasic IL, [P<sub>66614</sub>][benzim], with CO<sub>2</sub>, H<sub>2</sub>O and two mixed CO<sub>2</sub>/H<sub>2</sub>O vapor regimes using NAPXPS.

## EXPERIMENTAL SECTION

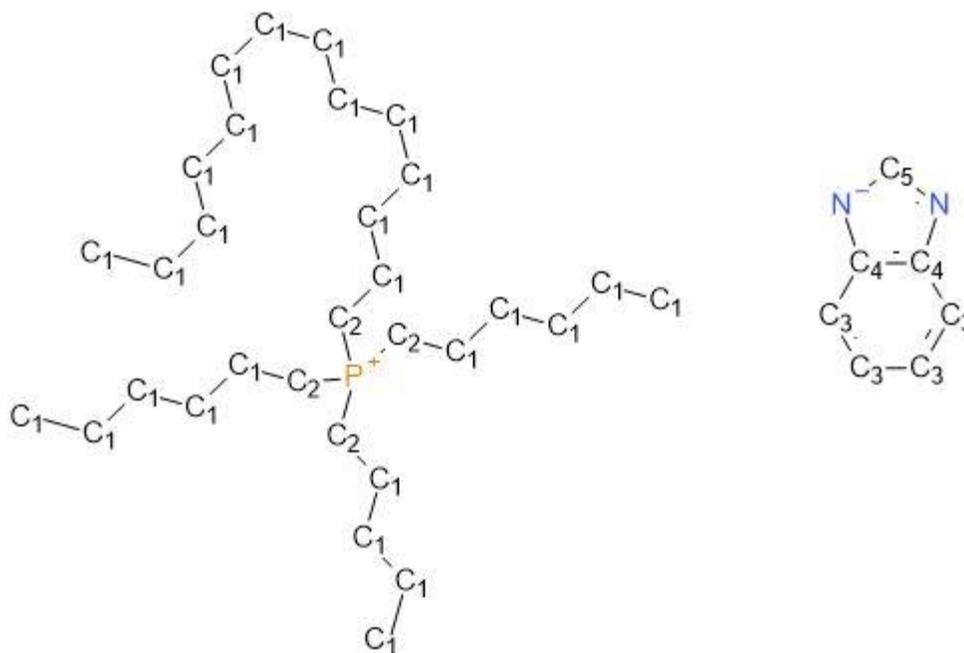
The SBIL, [P<sub>66614</sub>][benzim] was prepared using a two-step synthesis, described previously<sup>6</sup>. The IL was dried under high vacuum (0.01 mbar at 50°C for 72 hours) and then transferred to a vial sealed with a rubber septum in a dry argon-filled glovebox prior to use. Around 0.5 ml of IL was deposited dropwise by syringe onto a Ta sample plate under ambient laboratory conditions. The plate was transferred to a vacuum load lock and the load lock pumped down and left to reach  $<1 \times 10^{-6}$  mbar before transferring to the analysis chamber. During the preparation process, the sample was exposed to ambient lab atmosphere for around 5 minutes.

XPS analysis was carried out in a custom-built SPECS system equipped with a near-ambient pressure (NAP) cell, monochromated Al K<sub>α</sub> X-ray source and SPECS Phoibos NAP150 hemispherical analyzer. CO<sub>2</sub> (CK Gases, purity 99.9995%) was further purified by passing it through a scrubber (SAES Microtorr) to remove trace impurities, particularly of CO. Doubly distilled water was purified by repeated freeze-thaw-pump cycles until no gas bubbles were observed in the water under a vacuum of  $1 \times 10^{-6}$  mbar. Spectra were recorded with electron emission normal to the surface from the top edge of the IL film to minimize the possibility of

sample charging. Normal emission and grazing emission XPS measurements were carried out in ultra-high vacuum (UHV) conditions (at a pressure of approximately  $10^{-9}$  mbar; see Supporting Information (SI)) before being transferred to the NAP cell. NAPXPS measurements were carried out over seven stages in the NAP cell, as outlined in Scheme 2. During Stage 1, measurements were recorded from the unexposed IL. In Stage 2, the IL was exposed to 0.5 mbar of  $\text{CO}_2$ . For Stage 3, the  $\text{CO}_2$  was pumped out of the NAP cell and measurements were taken when the pressure had stabilized at approximately  $10^{-8}$  mbar, i.e. the IL was under high-vacuum conditions once again. Measurements taken at Stages 1 through 3 were to determine whether or not the  $\text{CO}_2$  capture by the IL was reversible through a pressure swing to reduced pressure. In the measurements taken after Stage 3, the IL is referred to as ‘regenerated’. Stage 4 involved exposing the regenerated IL to 3 mbar of  $\text{CO}_2$ . In Stage 5, 2 mbar  $\text{H}_2\text{O}$  vapor was introduced into the NAP cell, creating the first mixed-gas regime. During Stage 6, the  $\text{CO}_2$  flow was turned off, leaving the IL exposed only to 2 mbar of  $\text{H}_2\text{O}$  vapor and measurements were taken when the pressure in the NAP cell had stabilized at 2 mbar. For the final stage, Stage 7, 3 mbar of  $\text{CO}_2$  was reintroduced into the system giving a total  $\text{CO}_2$  and water pressure of 5 mbar for the second mixed-gas regime.



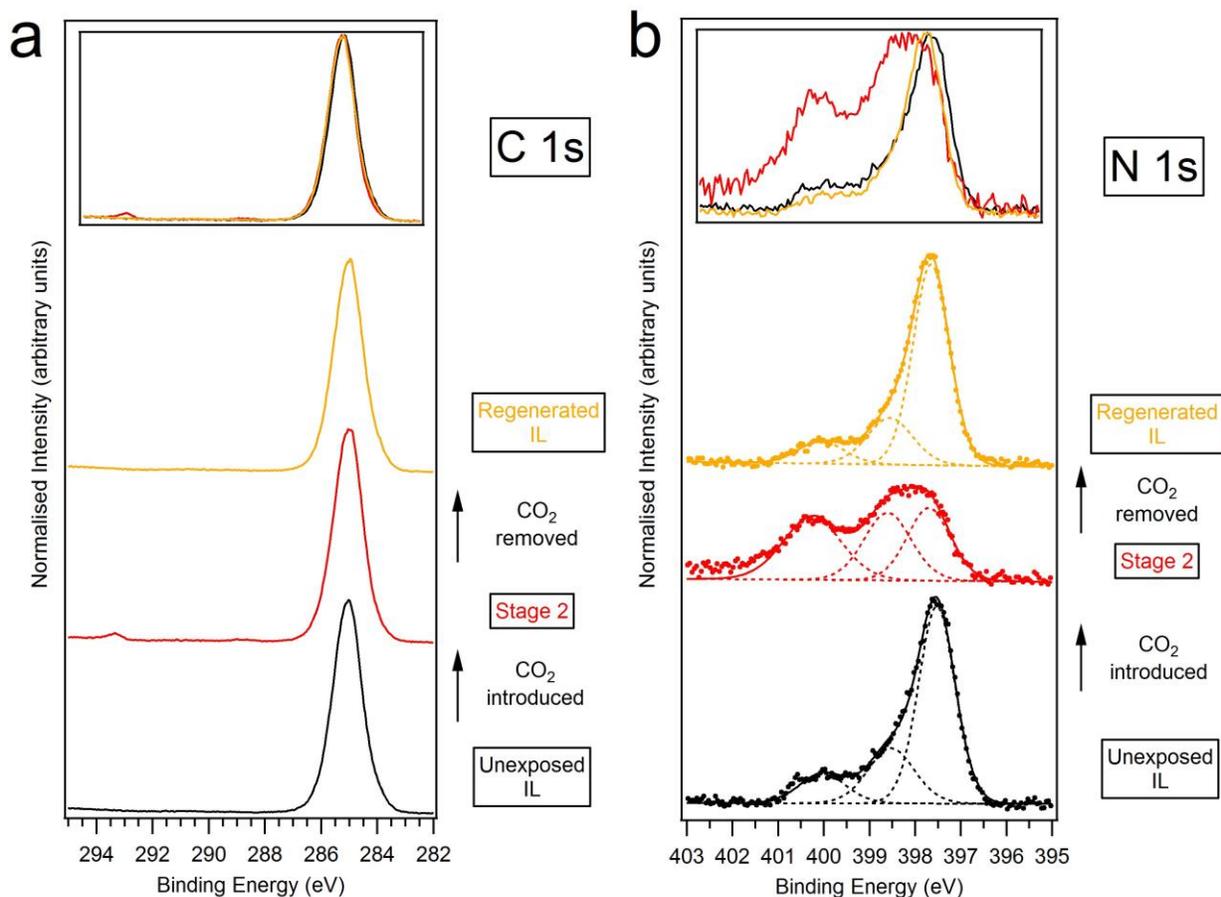
**Scheme 1.** Flow chart illustrating the stages of the experiment, numbered 1 to 7. The annotations between the stages describe which gases are introduced or removed. Measurements were taken at each stage.



**Figure 1.** Ball-and-stick diagram showing the structure of the superbasic IL, trihexyl-tetradecylphosphonium benzimidazolide, or  $[P_{66614}][\text{benzim}]$ . The labels  $C^1$  to  $C^5$  highlight the different chemical environments of the carbon atoms present in the IL pair.

Each NAPXPS spectrum was recorded from a different position on the sample surface to avoid damage due to prolonged X-ray exposure. Each measurement took approximately one hour, and all measurements were taken at room temperature. Spectra are aligned on the binding energy (BE) scale relative to the aliphatic C 1s signal at 285.0 eV<sup>28</sup>, with all BEs quoted to  $\pm 0.1$  eV. XPS core level peak fitting was carried out using CasaXPS software with a linear baseline and 70:30 Gaussian:Lorentzian lineshape<sup>29</sup>.

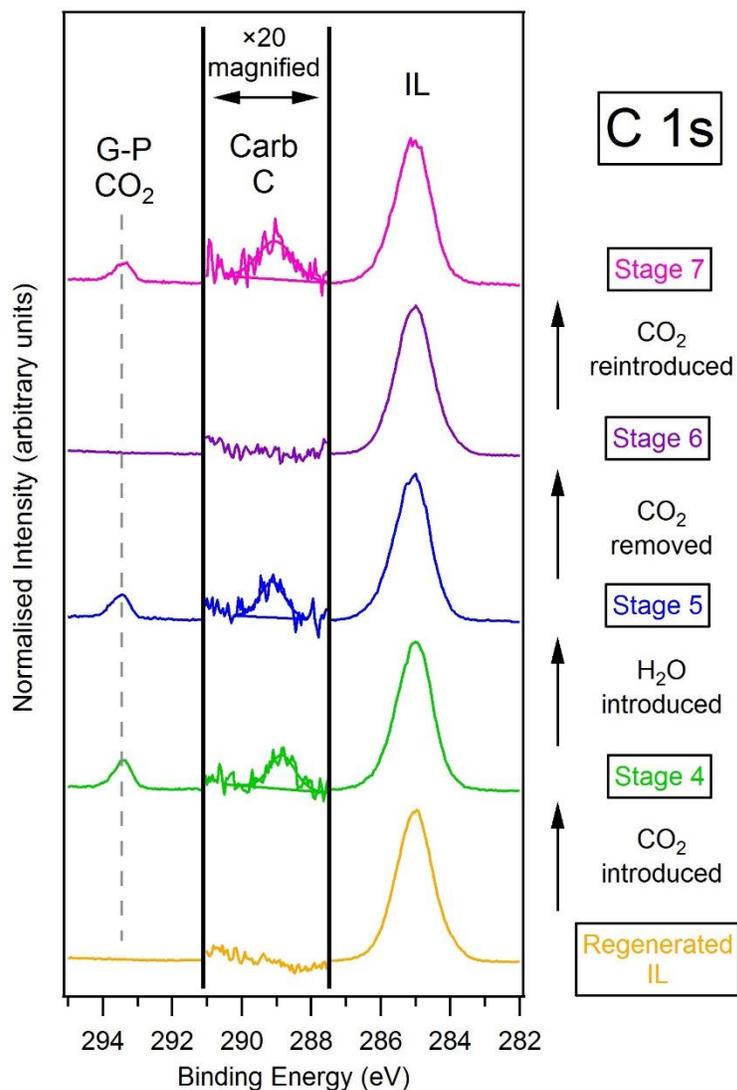
## RESULTS AND DISCUSSION



**Figure 2.** The C 1s region (a), and N 1s region (b) of the unexposed IL (Stage 1, black line), of the IL during exposure to 0.5 mbar of CO<sub>2</sub> (Stage 2, red line), and of the regenerated IL (Stage 3, amber line). Each N 1s spectrum has been normalized to the total area, and each C 1s spectrum has been normalized to the IL carbon peak. The intensity of the spectra in the inset figures have been normalized to the most intense peak.

The C 1s and N 1s photoelectron spectra recorded from the IL during Stages 1 through 3 are shown in Figure 2, represented by the black, red and amber lines, respectively. In each region, the spectrum post-exposure is almost identical to the spectrum of the unexposed IL (see inset of Figure 2a and Figure 2b). This demonstrates that any interaction between the IL and CO<sub>2</sub> is reversible when the pressure in the NAP cell is reduced. Furthermore, these data suggest that the

IL can be largely regenerated through a reduction in pressure. The C 1s shows very little discernible change upon exposure to 0.5 mbar CO<sub>2</sub> and following regeneration by evacuation of the gas cell (see inset of Figure 2a). The N 1s, however, shows more significant changes in the presence of the gas with a broadening of the peak near 397.5 eV and the growth of a second feature at around 400 eV. The peak at 397.5 eV, which dominates the spectrum recorded from the unexposed film, is attributed to the nitrogen atoms of the [benzim]<sup>-</sup> anion (labelled N<sub>Im</sub> in Figure 4). Due to resonance effects the two N atoms in the [benzim]<sup>-</sup> anion can be considered chemically equivalent<sup>16-17</sup>. The small feature at around 400 eV has been attributed to the presence of protonated benzimidazole. The growth of this peak and the associated broadening of the lower binding energy feature on exposure to CO<sub>2</sub>, coupled with the loss of these features on removal of CO<sub>2</sub>, indicate these features are associated with the interaction with CO<sub>2</sub>. In order to investigate the origin of these features the regenerated IL was exposed to CO<sub>2</sub> and H<sub>2</sub>O in stages as described above.



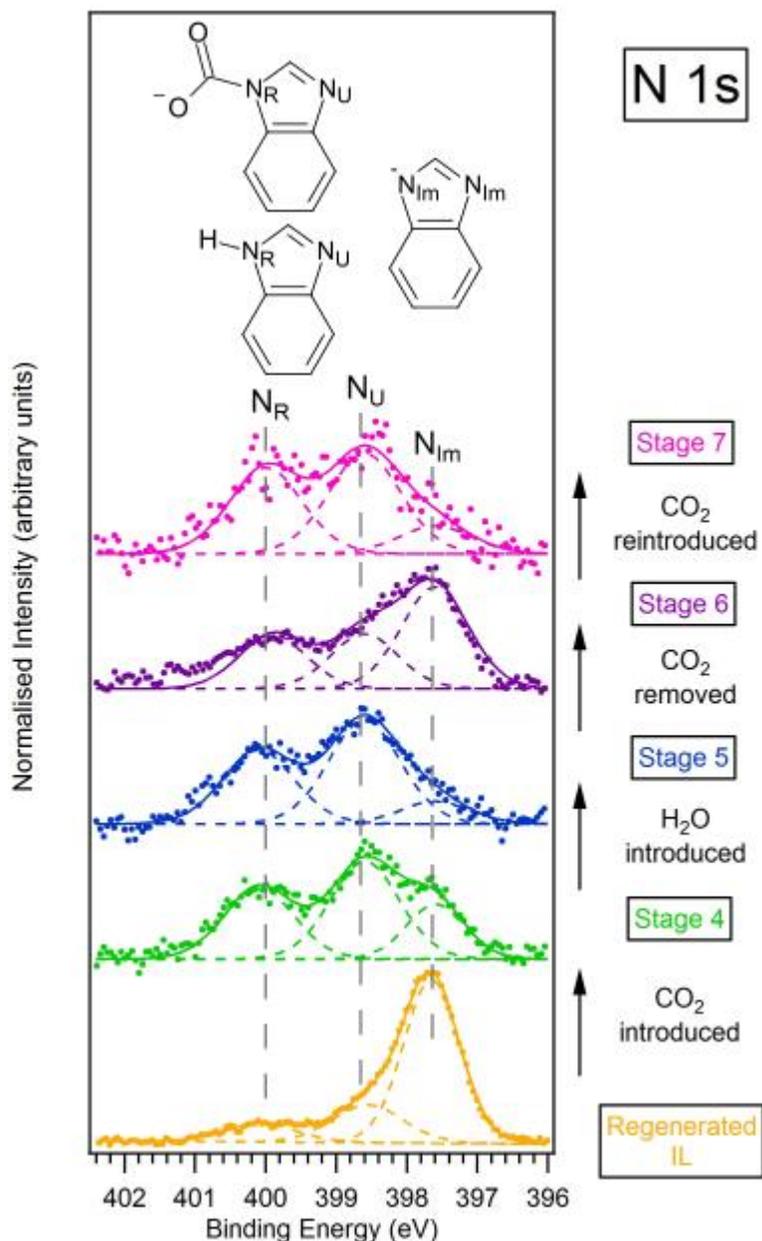
**Figure 3.** C 1s spectrum taken of the regenerated IL (Stage 3, amber line), of the IL during exposure to 3 mbar CO<sub>2</sub> (Stage 4, green line), during exposure to the first mixed-gas regime (Stage 5, blue line), during exposure to 2 mbar H<sub>2</sub>O (Stage 6, violet line), and during exposure to the second mixed-gas regime (Stage 7, magenta line). The data between 291.0 eV and 287.5 eV is  $\times 20$  magnified. The term gas-phase is abbreviated to ‘G-P’, and carbamate is shortened to ‘Carb’.

Figure 3 shows the C 1s spectra recorded through Stages 3 to 7. All of the C 1s spectra feature a strong, slightly asymmetric signal at 285.0 eV. This signal is attributed to the carbon atoms in [P<sub>66614</sub>][benzim]. Blundell and Licence<sup>28</sup> studied other ILs with the same cation using XPS. They resolved the asymmetrical peak associated with the [P<sub>66614</sub>]<sup>+</sup> cation into two components: one attributed to the hetero (C-P) carbon, and one attributed to the alkyl (C-C) carbon (the hetero carbons and alkyl carbons are labelled as C<sup>2</sup> and C<sup>1</sup> respectively in Figure 1). The C 1s signal in this work will consist of contributions from these carbon environments, in addition to contributions from the aromatic carbon species of the anion (labelled C<sup>3</sup> to C<sup>5</sup> in Figure 1). However, none of the contributions from either the cation or the anion have been fitted here, since fitting any components to this peak would be speculative at best given the broad nature of the peak. Upon exposure to 3 mbar CO<sub>2</sub> (Stage 4, represented by the green line), two more signals appear in the region. The peak at a BE of 293.4 eV is attributed to gas phase CO<sub>2</sub> and the peak observed at a BE of approximately 289.0 eV is attributed to carbamate formation<sup>30</sup>. These peaks do not change significantly in shape upon exposure to water during the first mixed-gas regime (Stage 5, represented by the blue line), but there is a slight upward shift in BE for the carbamate CO<sub>2</sub> peak from 288.8 eV to 289.1 eV. In numerous studies, the BE of peaks associated with ad/absorbed gas species tend to shift with increased coverage (in the case of adsorbates), or increased gas pressure<sup>31-34</sup>. Since the IL was subject to further CO<sub>2</sub> exposure during Stage 5, it is, therefore, likely that this shift is due to an increase in absorbed CO<sub>2</sub> in the IL. During Stage 6 (2 mbar H<sub>2</sub>O vapor only, represented by the violet line), the signal attributed to carbamate CO<sub>2</sub> is no longer present, indicating desorption of CO<sub>2</sub> from the IL. When 3 mbar of CO<sub>2</sub> is then reintroduced into the NAP cell (Stage 7, represented by the magenta line), the

peak at  $\sim 289.0$  eV returns, with a similar intensity to that seen in Stage 5. The peak assignments are summarized in Table 1.

**Table 1.** Binding energies and assignments of all peaks in the C 1s, O 1s, and N 1s regions throughout the experiment.

Region	Binding Energy (eV) ( $\pm 0.1$ eV)	Assignment
	285.0	IL C
C 1s	289.0	Carbamate C
	293.4	Gas-phase CO <sub>2</sub>
	397.5	Imidazolide N
N 1s	398.5	Unreacted N
	400.0	Reacted N



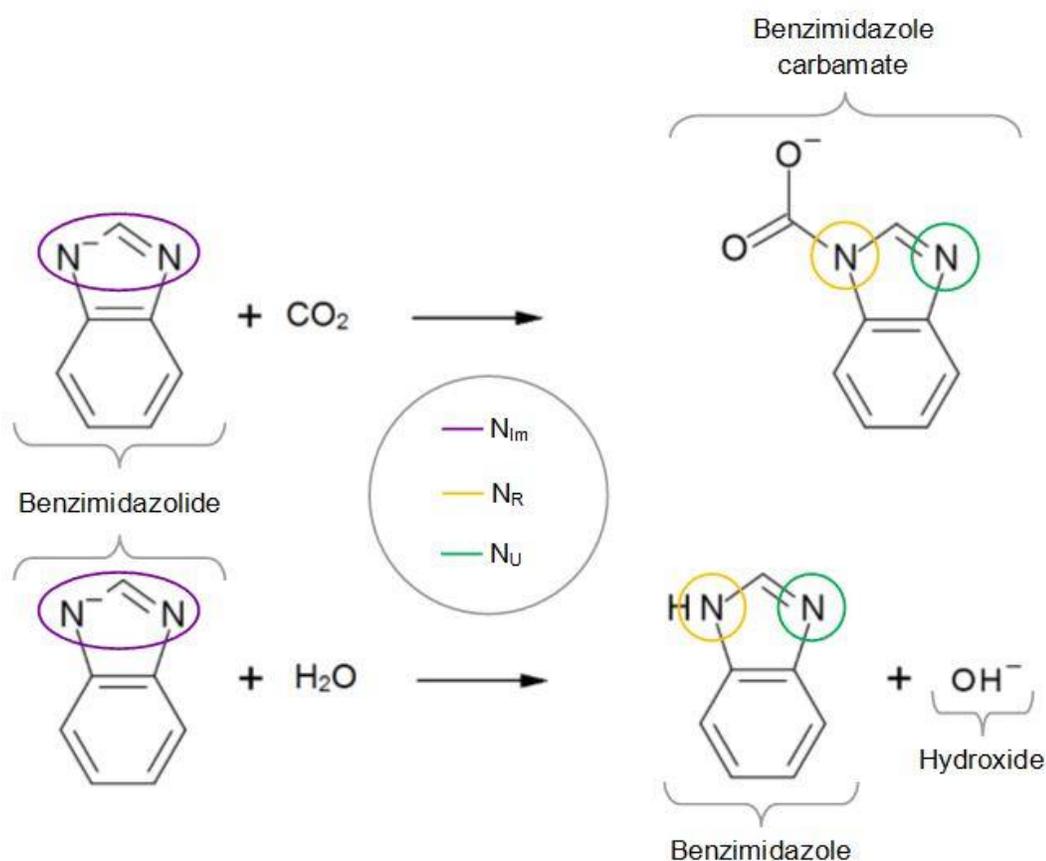
**Figure 4.** N 1s spectrum taken of the regenerated IL (Stage 3, amber line), of the IL during exposure to 3 mbar CO<sub>2</sub> (Stage 4, green line), during exposure to the first mixed-gas regime (Stage 5, blue line), during exposure to 2 mbar H<sub>2</sub>O (Stage 6, violet line), and during exposure to the second mixed-gas regime (Stage 7, magenta line). The label  $N_{Im}$  refers to the imidazolidine N. The labels  $N_U$  and  $N_R$  refer to the unreacted and reacted N respectively. Each spectrum has been normalized to the total area of the region. Chemical structures of an ordinary [benzimidazole]<sup>-</sup> anion

(with N atoms labelled  $N_{Im}$ ) and reacted [benzim]<sup>-</sup> anions (with N atoms labelled  $N_U$  and  $N_R$ ) are featured above the spectra.

Figure 4 shows the N 1s spectrum through Stages 3 to 7 of the experiment. The spectrum of the regenerated IL (amber line) can be fitted with three peaks at binding energies of 397.5 eV, 398.5 eV and 400.0 eV. The peak at 397.5 eV is assigned to the imidazolide N atoms, as described above. The two peaks at higher BE are seen to increase in intensity when the IL is exposed to 3 mbar of CO<sub>2</sub> in Stage 4 (green line). They are, therefore, attributed to the reaction between the IL and CO<sub>2</sub>. The peak at 400 eV is attributed to the formation of carbamate, and has been labelled  $N_R$ , to mean ‘reacted’ N. Once a [benzim]<sup>-</sup> anion has reacted with CO<sub>2</sub>, the N atoms in the anion can no longer be considered as chemically equivalent. The reaction of the imidazolide ion with CO<sub>2</sub> will also mean the two N atoms in the anion will have a different charge density and therefore a different BE. As a result, the signal at 398.5 eV is attributed to a BE shift in this ‘unreacted’ N atom in the [benzim]<sup>-</sup> anion that has reacted with CO<sub>2</sub> (labelled  $N_U$  in Figure 4).

When 2 mbar of H<sub>2</sub>O is introduced to create the first mixed-gas regime (Stage 5, blue line), the  $N_U$  and  $N_R$  peaks continue to increase in intensity. This is likely to be due to continued reaction with CO<sub>2</sub>, reaction between the IL and H<sub>2</sub>O, or a combination of both. Imidazolide-based anions react with water to form an imidazole (protonated imidazolide) and a hydroxide anion (OH<sup>-</sup>)<sup>35</sup> (see Scheme 3). This reaction is seen in <sup>1</sup>H NMR spectra of [P<sub>66614</sub>][benzim]/H<sub>2</sub>O mixtures, manifesting as a downward chemical shift<sup>6</sup>. Morales-Gil *et al.*<sup>36</sup> reported that for mercaptobenzimidazole a BE difference of 1.6 eV between pyridine-like (N) and the pyrrole-like (NH) nitrogen atoms. This BE difference is consistent with the BE difference between our  $N_U$

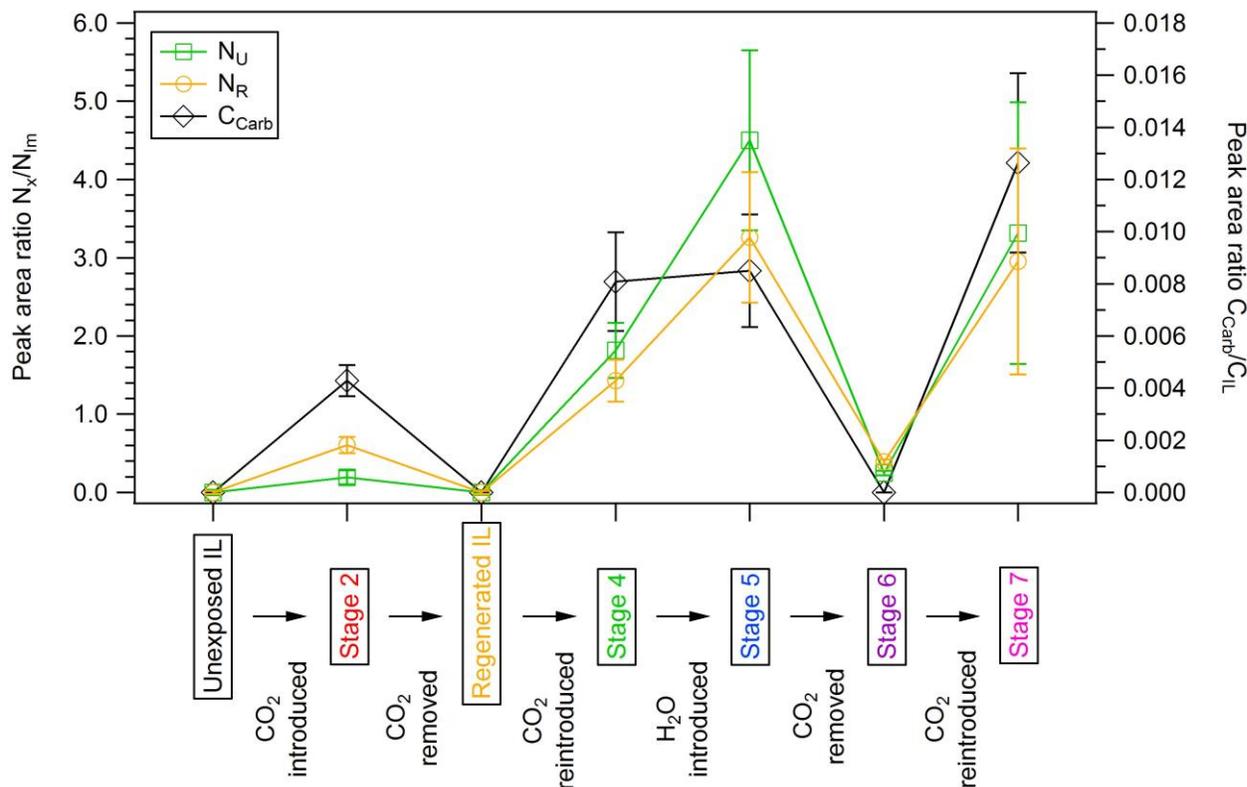
and  $N_R$  peaks. In addition, Tenney *et al.*<sup>4</sup> showed only a small shift of 0.3 eV BE between the carbamate N and protonated N in an XPS study of 3-amino-1-propanol and  $\text{CO}_2$ . Therefore, on exposure to water we attribute the additional intensity of the  $N_U$  and  $N_R$  peaks to unreacted (non-protonated) N and reacted (protonated) N, respectively, as a result of the reaction between the IL and  $\text{H}_2\text{O}$ . To clarify, the  $N_R$  peak is attributed to a combination of  $\text{N-COO}^-$  and  $\text{NH}$  signals, and the  $N_U$  peak is attributed to the unreacted N atom in the ring of a ‘reacted’ anion.



**Scheme 2.** Proposed reaction between a benzimidazolide ( $[\text{benzim}]^-$ ) anion and  $\text{CO}_2$  (top), generating a carbamate group bound to the previously negatively-charged N, forming benzimidazole carbamate. The proposed reaction between a benzimidazolide anion and  $\text{H}_2\text{O}$  is shown (bottom), where the anion is protonated (forming imidazole) and generates a hydroxide

anion. The violet circles highlight the imidazolide N (labelled  $N_{Im}$ ), the amber circles highlight the reacted N of both the carbamate and imidazole (labelled  $N_R$ ), and the green circles highlight the unreacted N of both reactions (labelled  $N_U$ ).

When the IL is exposed to only 2 mbar  $H_2O$  (Stage 6), the  $N_U$  and  $N_R$  peaks both decrease in intensity. This further supports the theory that the IL can be regenerated through a reduction in surrounding  $CO_2$  partial pressure. The intensities of these peaks, however, do not completely return to the same values as those from the regenerated IL, confirming that there is an interaction between the IL and  $H_2O$  vapor. Since the  $N_U$  and  $N_R$  peaks are much less intense when only exposed to  $H_2O$ , this seems to indicate a preferential reaction with  $CO_2$  over  $H_2O$ . During the second mixed-gas regime (Stage 7), when the IL is exposed to 2 mbar  $H_2O$  and 3 mbar  $CO_2$  once again, the  $N_U$  and  $N_R$  peaks increase in intensity, with similar peak area ratios as those in Stage 5. From the assignments above one would expect that the  $N_R$  and  $N_U$  peaks should have a roughly equal intensity.

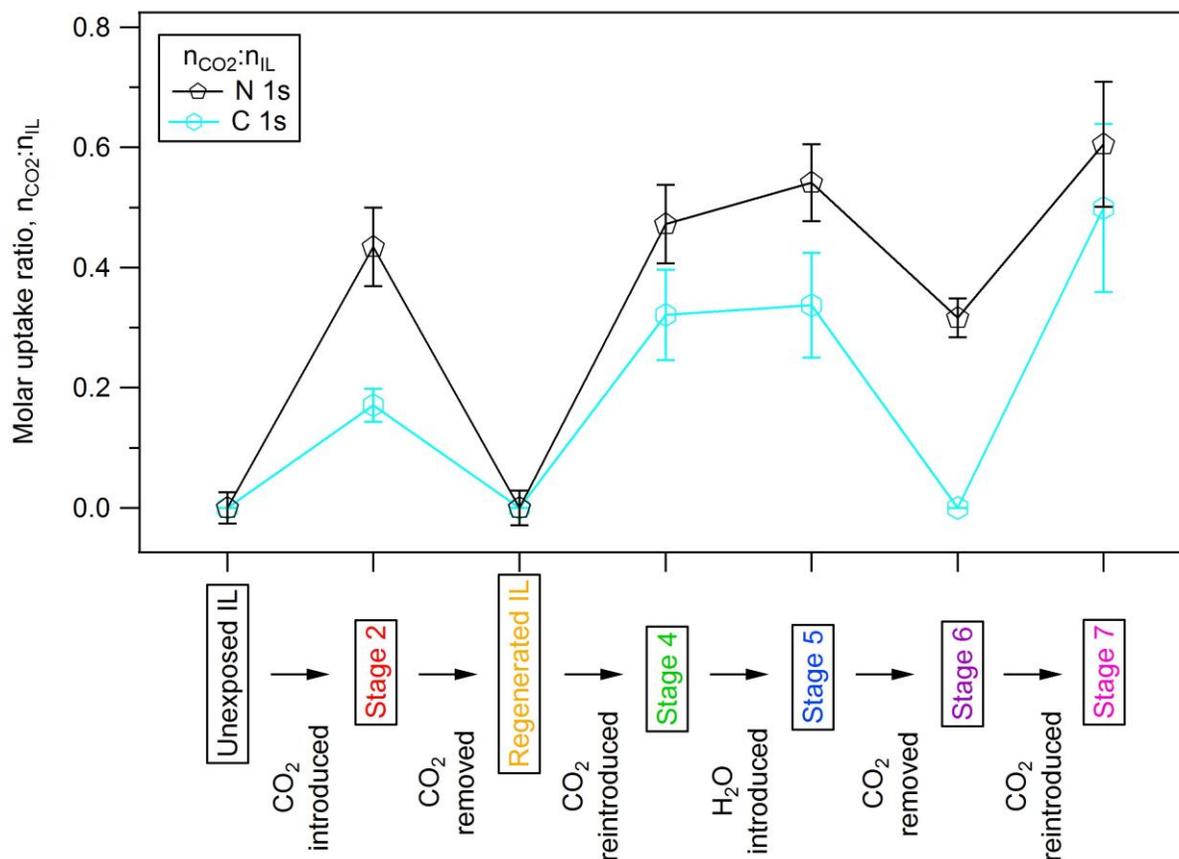


**Figure 5.** Displayed on the left axis: peak area ratios of  $N_U/N_{Im}$  (green squares) and  $N_R/N_{Im}$  (amber circles), where  $N_U$  refers to unreacted nitrogen,  $N_R$  refers to reacted nitrogen, and  $N_{Im}$  refers to imidazolide nitrogen. Displayed on the right axis: the peak area ratio of  $C_{Carb}/C_{IL}$  (black diamonds), where  $C_{Carb}$  refers to carbamate carbon, and  $C_{IL}$  refers to IL carbon.

Figure 5 shows the peak area ratios of  $N_U/N_{Im}$  and  $N_R/N_{Im}$  for each stage of experiment. The peak area ratios were calculated by dividing the area of the  $N_U$  or  $N_R$  peak by the area of the  $N_{Im}$  peak at each stage. The  $N_U$  and  $N_R$  peaks in the N 1s spectra for the unexposed IL and the regenerated IL have been accounted for in the calculations for the ratios calculated for Stages 2, and Stages 4 to 7. Specifically, the areas of the  $N_U$  and  $N_R$  peaks from the unexposed IL and the regenerated IL have been subtracted from the areas of the  $N_U$  and  $N_R$  peaks from later stages. Through Stages 3 to 7, it can be seen that  $N_U/N_{Im} > N_R/N_{Im}$ . This means the area of the  $N_U$  peak

is consistently greater than that of  $N_R$  throughout these stages, which means a peak area ratio of 1:1 is not maintained. The reasons for this are unclear. One possibility is that some of the absorbed  $CO_2$ , rather than forming a carbamate group, weakly interacts with the benzimidazolidine anion, causing a shift in the imidazolidine N peak to a higher BE. This could account for the consistently greater intensity of  $N_U$  compared to  $N_R$ , since increased gas exposure would lead to more  $CO_2$  absorption (via both physisorption and chemisorption) and a greater number of these weak interactions between the anion and  $CO_2$  molecules. It is possible that X-ray beam damage occurs, although this is usually indicated by the presence of a feature at low binding energy ( $\sim 397$  eV)<sup>16</sup>. From the data here, it is not possible to unambiguously identify the origin of this apparent discrepancy. Further work utilizing angle resolved photoemission, (to vary the depth) and near edge X-ray absorption fine structure may prove useful in elucidating the source of the increased intensity. The peak area ratio  $C_{Carb}/C_{IL}$  at each stage of the experiment is shown on the right axis of Figure 5. The C 1s peak intensities are normalized to the IL carbon peak, allowing for comparison of changes in the carbamate carbon peak intensity throughout the experiment. This ratio describes the change in intensity of the carbamate signal only, while both of the ratios of  $N_U/N_{Im}$  and  $N_R/N_{Im}$  describe intensity changes associated with both carbamate formation and benzimidazole formation.  $C_{Carb}/C_{IL}$  does not increase as significantly as  $N_U/N_{Im}$  or  $N_R/N_{Im}$  when the IL is exposed to  $H_2O$  in the first mixed gas regime (Stage 5). This confirms that the increase in  $N_U$  and  $N_R$  from Stage 4 to Stage 5 is largely due to the reaction with water.  $C_{Carb}/C_{IL}$  decreases significantly when the IL is exposed to only  $H_2O$  (Stage 6), which reflects the trend displayed by both  $N_U/N_{Im}$  and  $N_R/N_{Im}$ . Once the IL is exposed to the second mixed-gas regime (Stage 7),  $C_{Carb}/C_{IL}$  increases, again reflecting the trend displayed by both  $N_U/N_{Im}$  and  $N_R/N_{Im}$ .

This supports the idea that the IL continues to react with CO<sub>2</sub> despite initially exposing the IL to H<sub>2</sub>O vapor.



**Figure 6.** Molar uptake ratio,  $n_{\text{CO}_2}:n_{\text{IL}}$ , at each stage of the experiment, calculated using the N 1s region (black pentagons) and the C 1s region (cyan hexagons).

The molar uptake ratio,  $n_{\text{CO}_2}:n_{\text{IL}}$  was calculated using the area of the  $N_R$  peak in the N 1s region, and the area of the whole N 1s region. For comparison, a separate value for the molar uptake ratio was calculated using the area of the carbamate peak and the area of the whole C 1s region (excluding gas-phase signals). Similarly to the N 1s area ratios, the  $N_U$  and  $N_R$  peaks from the unexposed IL and regenerated IL have been accounted for in the calculation of the molar

uptake ratio at each Stage. These values of  $n_{\text{CO}_2:n_{\text{IL}}}$  at each stage have been plotted in Figure 6. In the study by Taylor et al<sup>6</sup>, they calculated the molar uptake ratio of  $\text{CO}_2$  in dry [P<sub>66614</sub>][benzim] (at saturation) to be 1.2. It is likely to be the case that the chemisorption of  $\text{CO}_2$  occurs 1:1, but can exceed capacity by ‘trapping’ physisorbed  $\text{CO}_2$ . It was found the addition of water reduced the molar uptake ratio of  $\text{CO}_2$  to 1, which indicates saturation of the IL with water diminishes its capacity for physisorbed  $\text{CO}_2$ . Throughout all stages of the experiment the ratio  $n_{\text{CO}_2:n_{\text{IL}}}$  is always  $<1$  which is expected since the imidazolide signal is always present in the N 1s region, and therefore some unreacted anions remain in the IL. The molar uptake ratio calculated using these regions follow a similar trend, but  $n_{\text{CO}_2:n_{\text{IL}}}$  for the C 1s region is always less than that calculated using the N 1s region at every stage. There are two reasons for this. Firstly, the reaction with  $\text{H}_2\text{O}$  leads to an increase in the intensity of the  $\text{N}_R$  peak. As a result, the molar uptake ratio calculated using the N 1s region is overestimated. Secondly, the presence of any contaminant C at the surface, likely as a part of silicon grease (see SI), has not been taken into account<sup>37-38</sup>. The signal would overlap with that of the IL, and so would contribute to the intensity of the IL carbon peak. This intensity inflation consequently reduces the apparent relative intensity of the carbamate peak, causing the molar uptake ratio calculated using the C 1s region to be underestimated. This would have a similar effect on the peak area ratio,  $C_{\text{Carb}}/C_{\text{IL}}$ , where the intensity inflation leads to a decrease in the ratio.

The values of  $n_{\text{CO}_2:n_{\text{IL}}}$  calculated using the N 1s region averages at  $\sim 0.5$ , irrespective of  $\text{CO}_2$  partial pressure. A consistent uptake ratio may be explained by the existence of a threshold of ‘surface saturation’, where reacted species move to the bulk of the IL, and a portion of unreacted species are present at the surface. An XPS investigation into the reaction between a solution of MEA and  $\text{CO}_2$  by Lewis *et al.*<sup>39</sup> demonstrated that the concentration of reacted species was

greater in the bulk of the solution, whereas the concentration of the unreacted MEA was greater at the surface. The IL film studied here is greater than the sampling depth of XPS (see SI), and is therefore considered a bulk system. It may be the case for [P<sub>66614</sub>][benzim] that the anions that have reacted with CO<sub>2</sub> move to the bulk of the IL, and unreacted anions become more prevalent at the surface of the IL. If a portion of unreacted species consistently populates the IL/CO<sub>2</sub> interface, this would facilitate continuous reaction between the IL and CO<sub>2</sub> until saturation. However, [P<sub>66614</sub>][benzim] is significantly more viscous than MEA<sup>6, 40-41</sup>, which is likely to hinder transport of reacted species in the IL. In previous studies, the IL was subject to saturation of CO<sub>2</sub>/H<sub>2</sub>O<sup>6</sup>, but at these pressures, we are predominantly investigating absorption phenomena via chemisorption due to changes in the N 1s following reaction between CO<sub>2</sub> and the IL. While physisorption of CO<sub>2</sub> cannot be ruled out, the C 1s and O 1s spectra recorded in this work cannot be deconvoluted sufficiently to determine the presence of physisorbed or absorbed CO<sub>2</sub>.

It is evident from the signals attributed to carbamate formation in both the C 1s and N 1s regions that IL continues to react with CO<sub>2</sub>, irrespective of whether it is exposed to CO<sub>2</sub> or H<sub>2</sub>O vapor first. This demonstrates that its ability to react is not significantly inhibited by exposure to H<sub>2</sub>O vapor. As mentioned previously, in the study by Taylor et al<sup>6</sup>, the capacity for chemisorbed CO<sub>2</sub> was maintained (i.e. 1:1 ratio of CO<sub>2</sub> molecules to IL pairs), but the capacity for physisorbed CO<sub>2</sub> ('trapped' CO<sub>2</sub>, the remaining 0.2 of the dry IL molar uptake ratio) was reduced. This is also reflected in our data, whereby the molar uptake ratio (which is likely to be dominated by chemisorption) is a similar value in both mixed-gas regimes, demonstrating that the capacity for chemisorption, under these conditions, was not significantly affected by initial exposure to H<sub>2</sub>O vapor. The peak area ratios  $N_U/N_{Im}$ ,  $N_R/N_{Im}$ , and  $C_{Carb}/C_{IL}$  in the second mixed-gas regime (Stage 7) are consistent with those in the first mixed-gas regime (Stage 5). This

means that the IL reacts with CO<sub>2</sub> and forms a similar proportion of carbamate groups irrespective of whether the IL has been exposed initially to H<sub>2</sub>O vapor or CO<sub>2</sub> gas. The idea that a similar number of carbamate groups formed in Stages 5 and 7 suggests that H<sub>2</sub>O does not displace CO<sub>2</sub>, but CO<sub>2</sub> molecules do displace the hydrogen bonds formed via the reaction between the IL and H<sub>2</sub>O.

In previous work,<sup>6</sup> the superbasic ILs were regenerated through heating to 80°C, and removing the desorbed CO<sub>2</sub> under a flow of N<sub>2</sub>.<sup>6</sup> The measurements discussed here have shown that [P<sub>66614</sub>][benzim] can be regenerated by reducing the CO<sub>2</sub> partial pressure surrounding it. This might also suggest that when working at such low pressures (compared to those employed by Taylor *et al.*) the IL is more easily deprotonated allowing the reaction with CO<sub>2</sub> to proceed. The measurements here clearly demonstrate that the CO<sub>2</sub> capture capabilities of superbasic ILs are not diminished after regeneration for both dry and pre-wetted superbasic ILs.

## CONCLUSION

In summary, the reaction of CO<sub>2</sub> with [P<sub>66614</sub>][benzim] has been studied by NAPXPS and indicates reaction between the CO<sub>2</sub> and benzimidazolide N atoms to form a carbamate species. The results obtained during exposure to both H<sub>2</sub>O vapor and CO<sub>2</sub> indicate that the ability of the IL to react with CO<sub>2</sub> is not inhibited significantly by the presence of H<sub>2</sub>O, and that CO<sub>2</sub> appears to preferentially bind to the IL, even after exposure to H<sub>2</sub>O vapor. The upper limit of the molar uptake ratio,  $n_{\text{CO}_2}:n_{\text{IL}}$ , is calculated to be approximately 0.5. Additionally, the CO<sub>2</sub> reaction with the anion appears to be reversible simply by reducing the surrounding CO<sub>2</sub> pressure, showing that [P<sub>66614</sub>][benzim] can be regenerated in situ.

## ASSOCIATED CONTENT

**Supporting Information.** X-ray photoelectron spectra (survey, C 1s, O 1s, N 1s, P 2p) under ultra-high vacuum conditions at normal and grazing emission, and *in situ* X-ray photoelectron spectra of the P 2p region.

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### Notes

The authors declare no competing financial interests.

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## ABBREVIATIONS

[P<sub>66614</sub>][benzim], trihexyl-tetradecylphosphonium benzimidazolide;

MEA, monoethanolamine;

NAPXPS, near-ambient pressure X-ray photoelectron spectroscopy;

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